大気ニュートリノ

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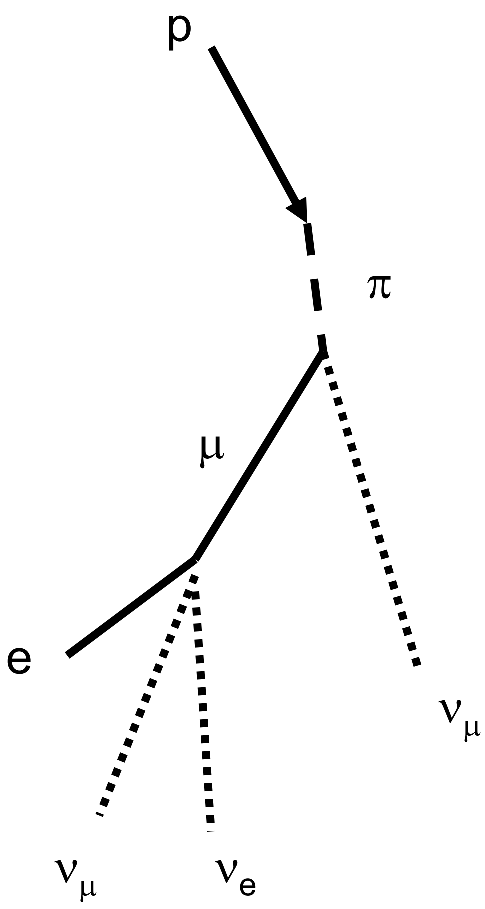
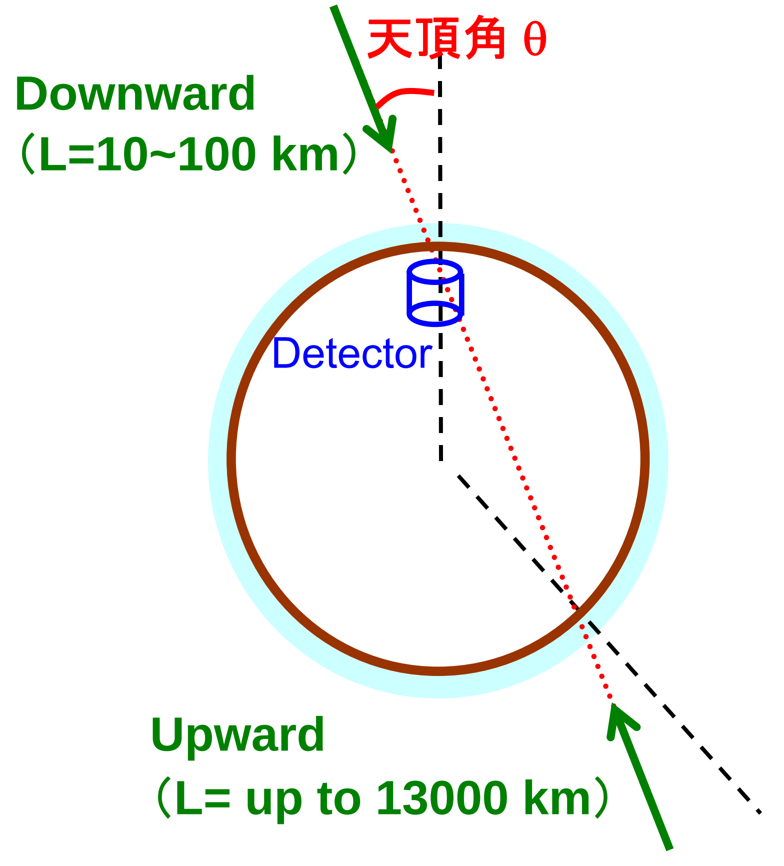
内容

- 大気ニュートリノについて
- SKにおける大気ニュートリノの結果
  1. 2 flavor analysis (太陽効果を含む)
  2. L/E analysis
  3. τ appearance
- Neutrino 2006 presentation
  1. MINOS
  2. SNO
- summary

大気ニュートリノ

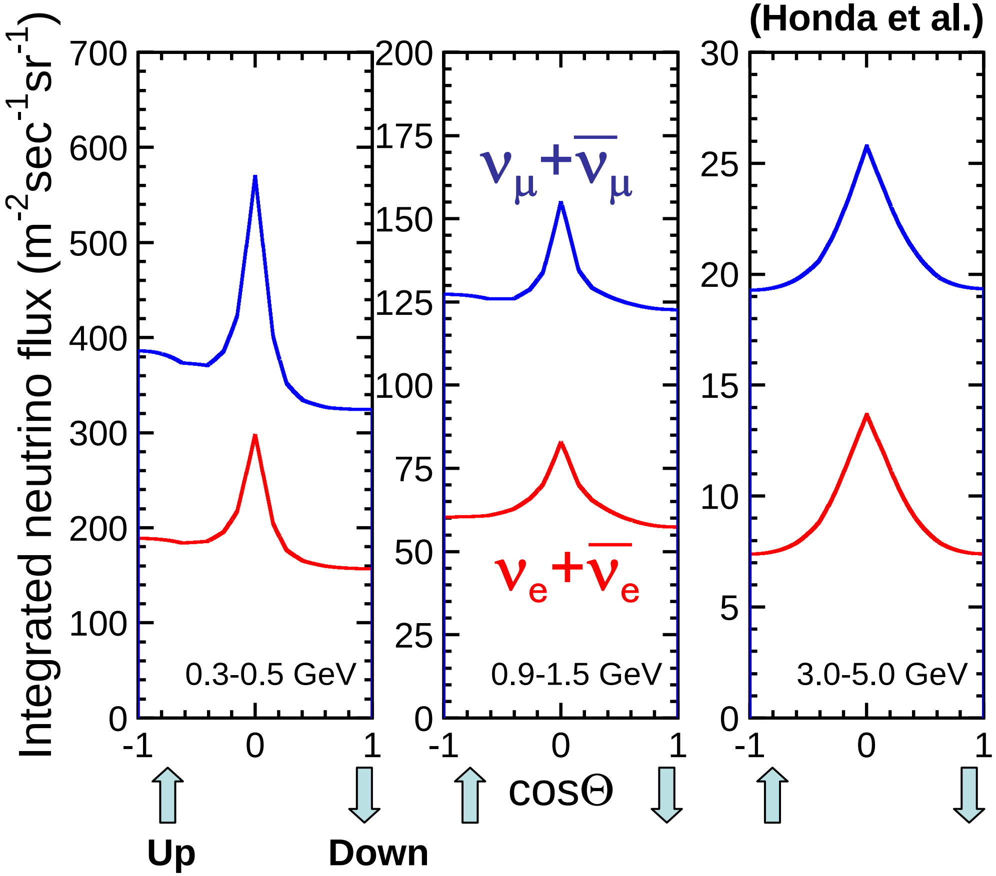


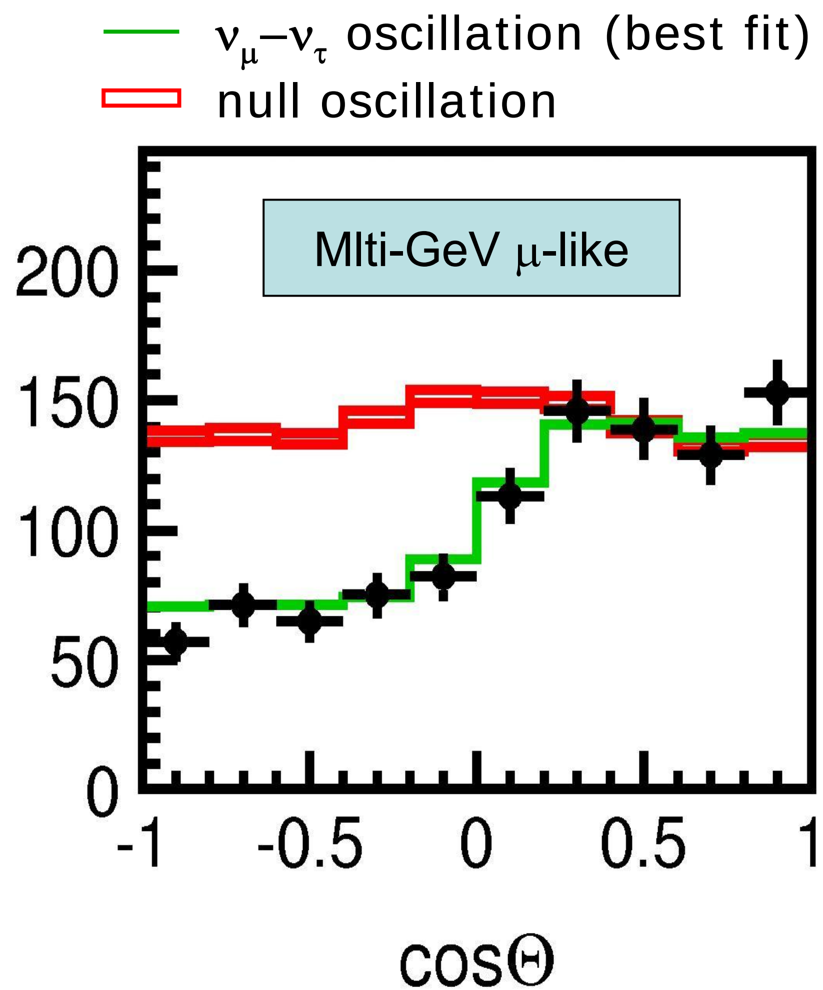


大気に降り注ぐ宇宙線(主に陽子)が大気と衝突してニュートリノを生成する。
それを検出器で捕まえる

天頂角分布

期待されるニュートリノフラックス





大気ニュートリノの天頂角分布はエネルギーの高いところ(数GeV以上)で上下対称になることが期待される(ニュートリノ振動が無い場合)

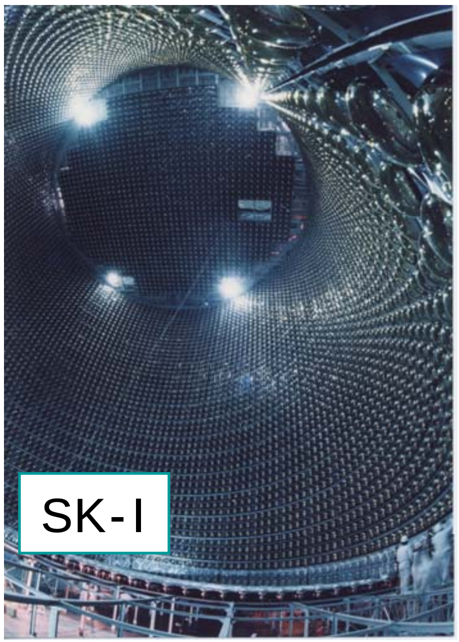
Data set

- Super-K I+II(全データ)
  SK-I (1489days) + SK-II (804days)
- MINOS
  418 live days (contained vertex events)
  842 live days (ν induced μ events)
- SNO
  149 days exposure

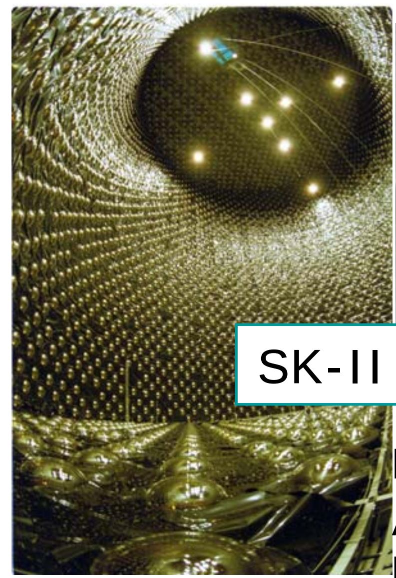
Super-Kamiokande

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007

SK-I — accident — SK-II — reconstruction — SK-III



- 50kton cylindrical water Cherenkov detector
  (22.5kt fiducial vol.)
- 1000m underground
  (2700m water equiv.)
- optically separated into ID and OD



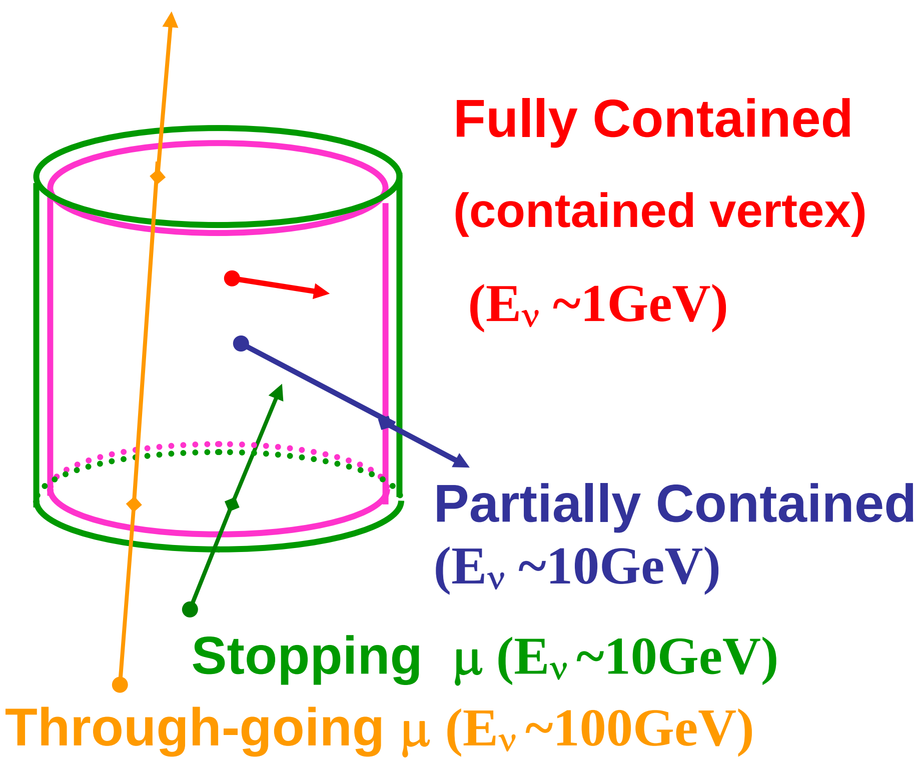
PMT enclosure :
Acrylic (front) and Fiberglass (back)

11146	Num. of inner detector PMTs	5182
40 %	Photocathod coverage	19 %

SK-III physics run will start in July 2006.

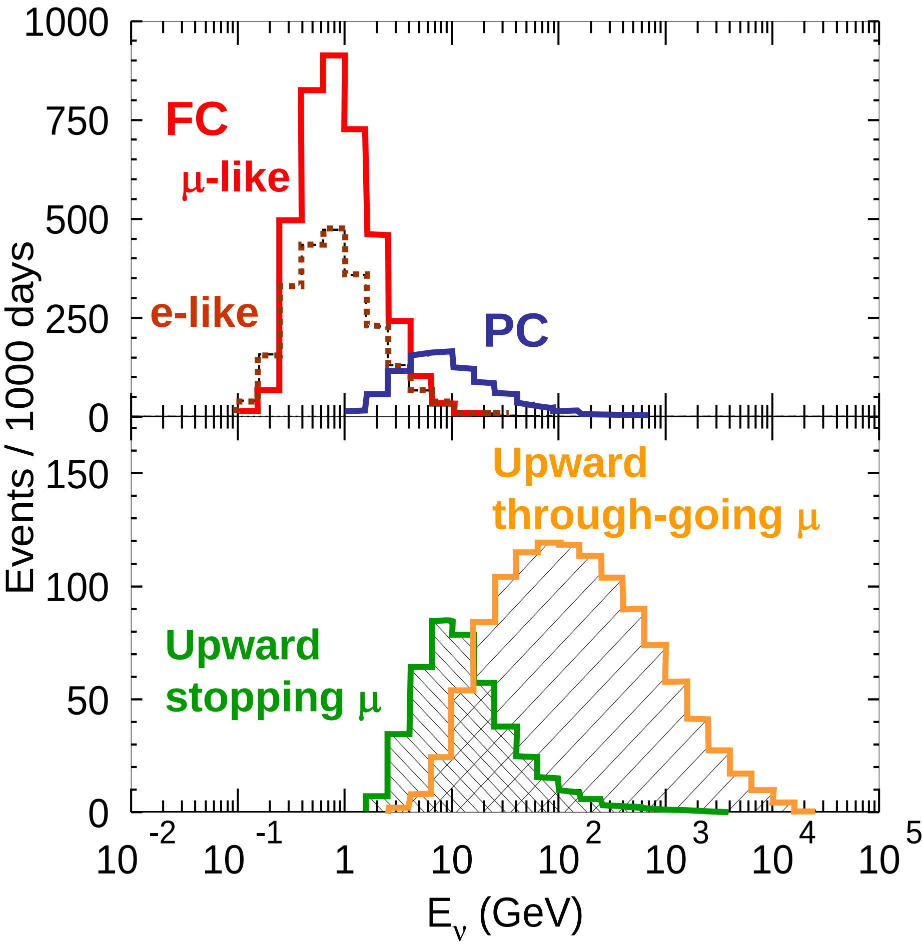
観測される大気ニュートリノ事象

イベントカテゴリー

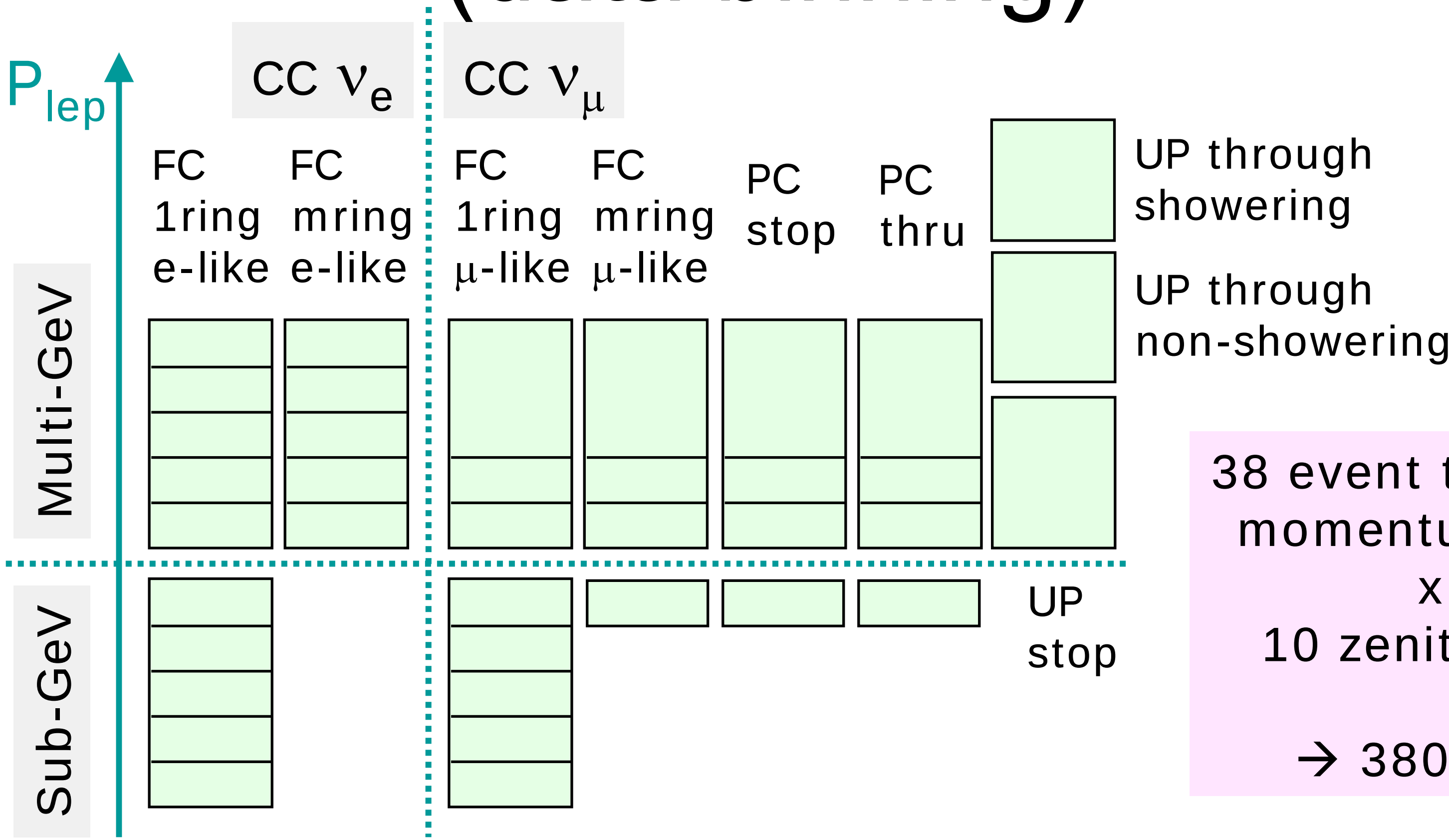


(neutrino induced muon events)

各サンプルでのニュートリノエネルギー



SK-I + SK-II combined analysis (data binning)



38 event type and momentum bins
x
10 zenith bins

→ 380 bins

Since various detector related systematic errors are different, we do not combine the SK-I and SK-II bins.

380 bins for SK-I + 380 bins for SK-II → 760 bins in total

SK-I + SK-II combined analysis (systematic errors)

neutrino flux (14)

neutrino interaction (12)

Identical for SK-I and SK-II

solar activity (1)

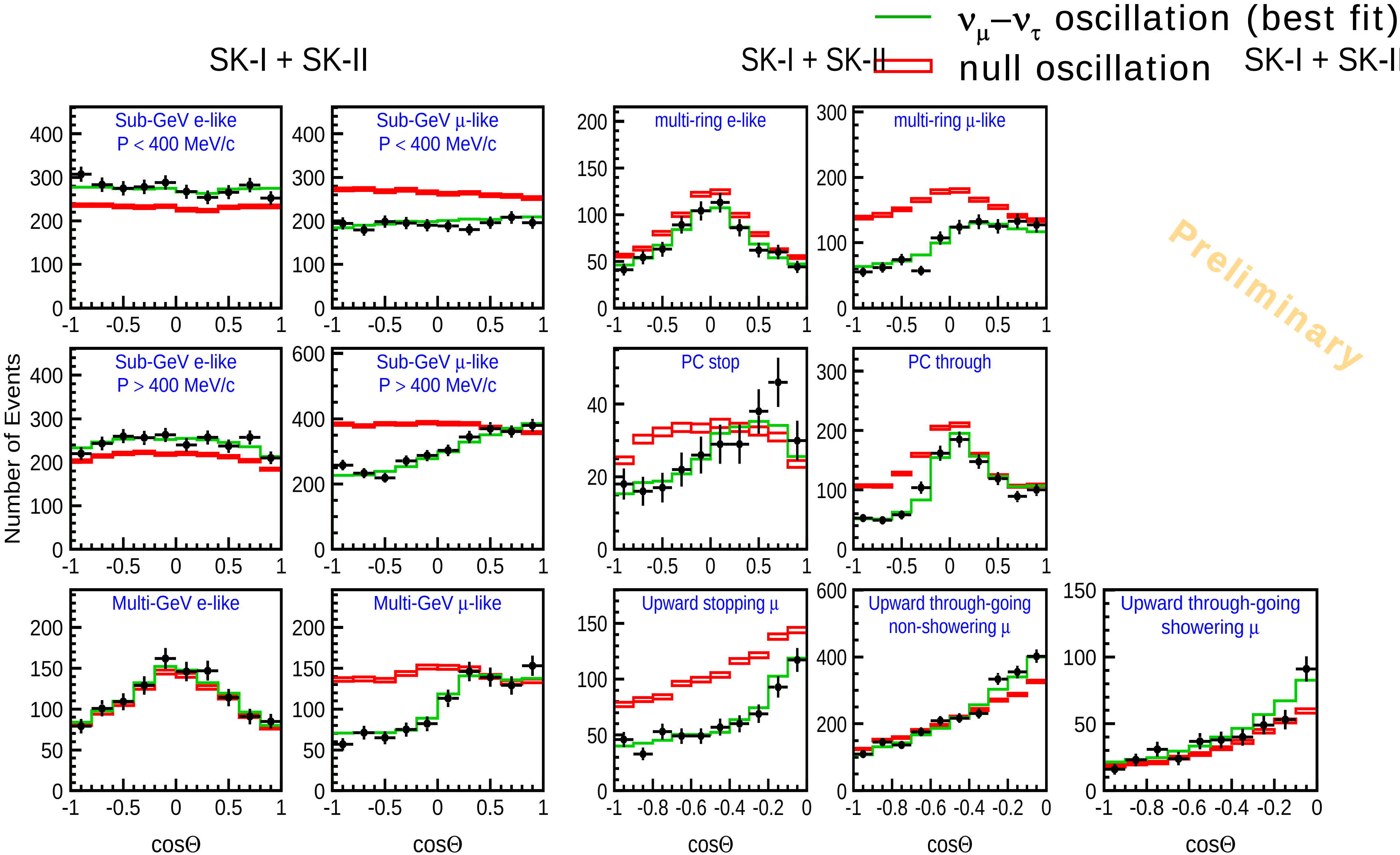
event selection
and reconstruction (21)

Regarded as independent between SK-I and SK-II

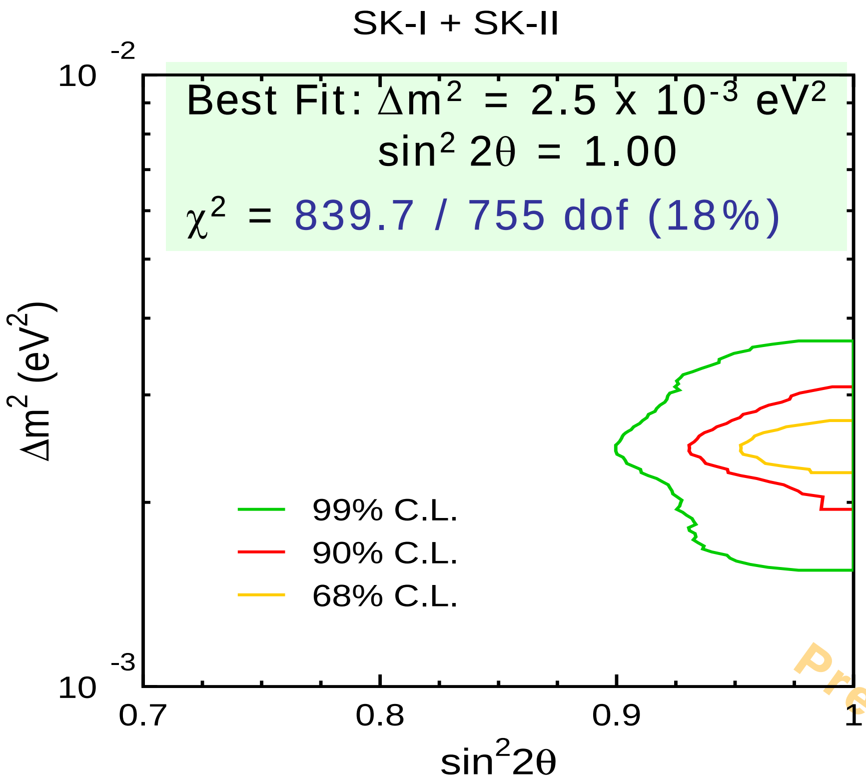
The total number of systematic errors is :

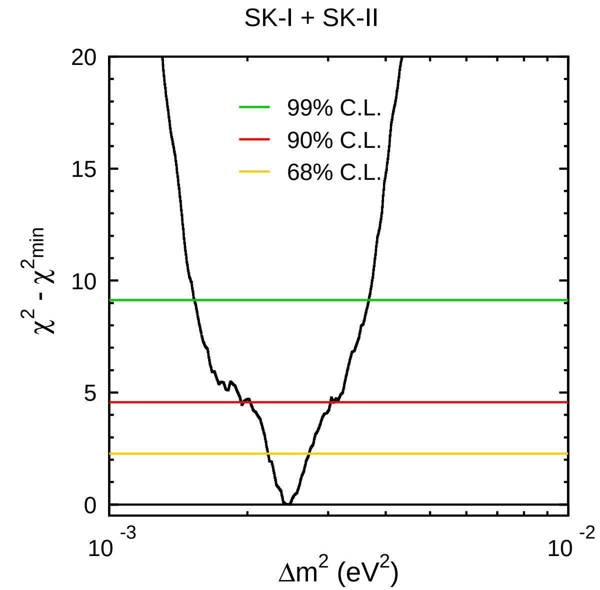
Flux (14) + Interaction (12) + SK-I (22) + SK-II (22) = 70

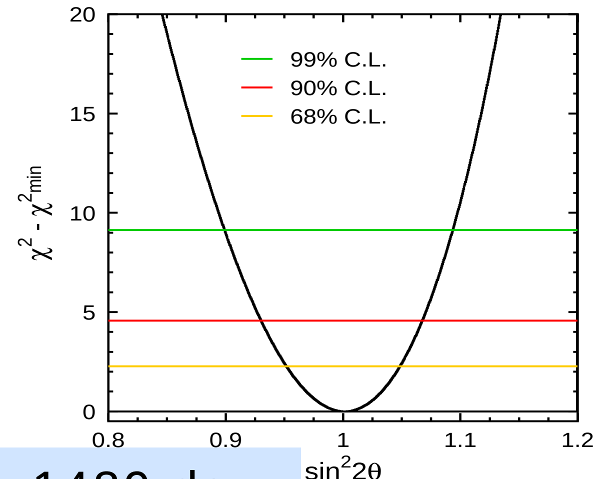
2 flavor analysis
Zenith Angle Distributions (SK-I + SK-II)



Result from SK-I + SK-II data







1.9 x 10^{-3} eV^2 < Δm^2 < 3.1 x 10^{-3} eV^2
$\sin^2 2\theta$ > 0.93 at 90% CL

SK-I : 1489 days
SK-II : 804 days

太陽効果 $\nu_\mu \rightarrow \nu_e$ Oscillation effects

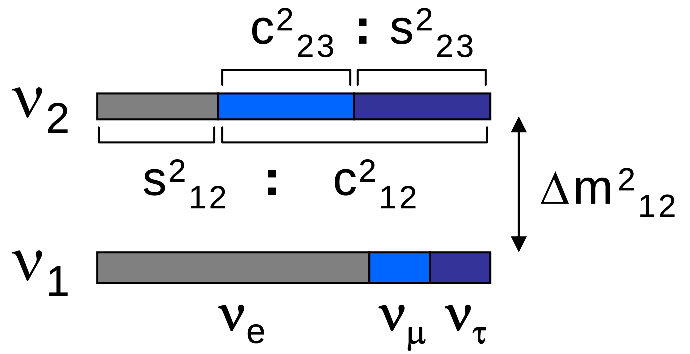
O. L. G. Peres and A. Yu. Smirnov, hep-ph/0309312

P_2 : 2ν transition prob. $\nu_e \rightarrow \nu_{\mu,\tau}$ in matter driven by Δm^2_{12}

$P(\nu_e \rightarrow \nu_e) = 1 - P_2$

$P(\nu_e \rightarrow \nu_\mu) = P(\nu_\mu \rightarrow \nu_e) = \cos^2\theta_{23} P_2$

$P(\nu_e \rightarrow \nu_\tau) = P(\nu_\tau \rightarrow \nu_e) = \sin^2\theta_{23} P_2$



ν_e decrease rate by ν_e oscillation : $1 - P(\nu_e \rightarrow \nu_e) = P_2$

ν_e increase rate by ν_μ oscillation : $r\,P(\nu_\mu \rightarrow \nu_e) = r\cos^2\theta_{23} P_2$

$r = \Phi^0(\nu_\mu) / \Phi^0(\nu_e) \sim 2$ (for low energy ν)

if $\cos^2\theta_{23} = 0.5$ ($\sin^2\theta_{23} = 0.5$) ν_e increase $\sim$ ν_e decrease

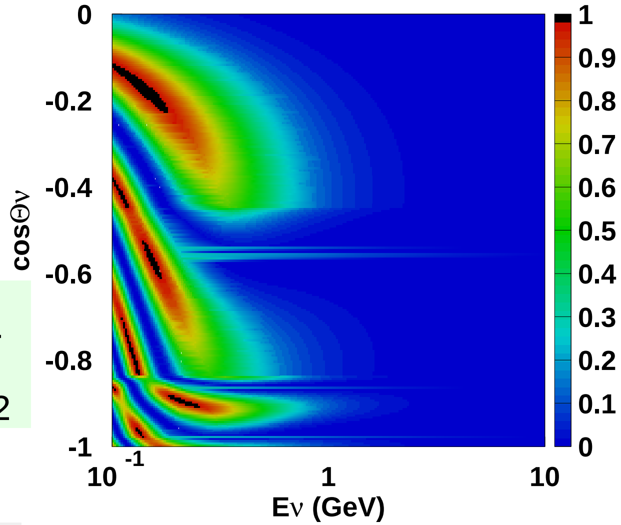
if $\cos^2\theta_{23} > 0.5$ ($\sin^2\theta_{23} < 0.5$) ν_e increase $>$ ν_e decrease

if $\cos^2\theta_{23} < 0.5$ ($\sin^2\theta_{23} > 0.5$) ν_e increase $<$ ν_e decrease

Solar term effect to atmospheric neutrinos

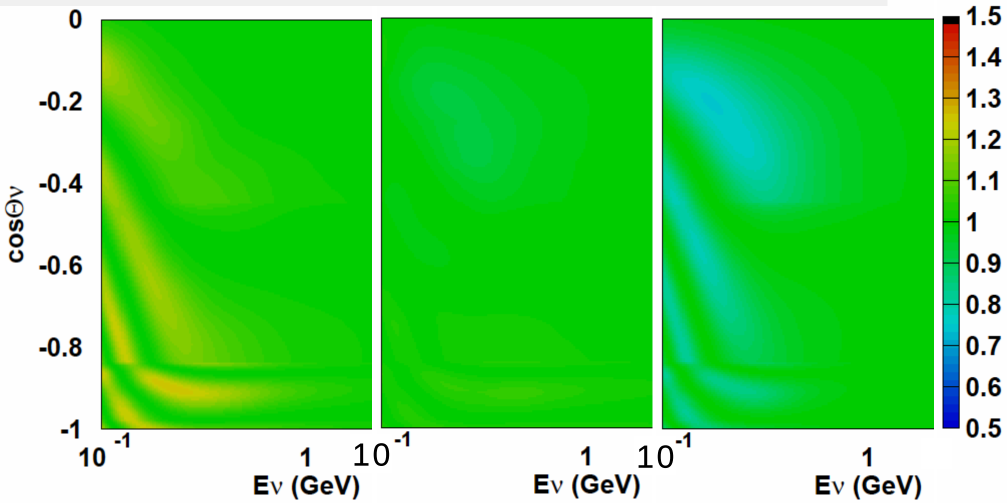
Due to the LMA solution, atmospheric neutrinos should also oscillate by (θ_{12} , Δm^2_{12}).

P_2 : 2ν transition prob. $\nu_e \rightarrow \nu_{\mu,\tau}$ in matter driven by Δm^2_{12}



$\sin^2 2\theta_{12}=0.83$
$\Delta m^2_{12}=8.3\text{x}10^{-3}$ (eV^2)
$\sin^2\theta_{13} = 0$

$\sin^2\theta_{23}$ = 0.4 = 0.5 = 0.6



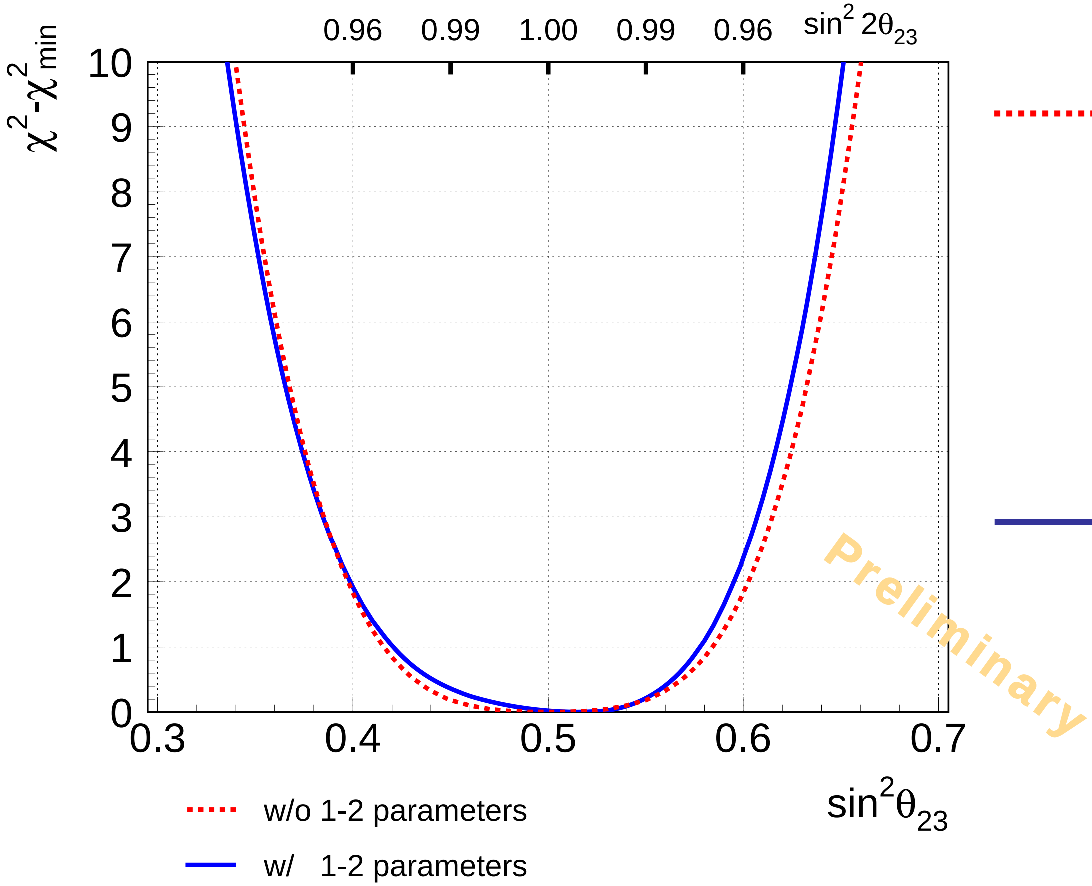
$$\frac{\nu_e \text{ flux (osc.)}}{\nu_e \text{ flux (no osc.)}}$$

Discrimination between $\theta_{23}<\pi/4$ and $>\pi/4$ might be possible by studying low energy atmospheric ν_e and ν_μ events.

Result of $\sin^2\theta_{23}$ determination (SK-I+II combined)

$\chi^2 - \chi^2_{min}$ distribution as a function of $\sin^2\theta_{23}$ where the other oscillation parameters are chosen to minimize χ^2

χ^2_{sol} from Solar-ν+KamLAND results are added in each $(\Delta m^2_{12}, \sin^2\theta_{12})$ point.



Solar terms off :

The 1-2 parameters $(\Delta m^2_{12}, \sin^2\theta_{12})$ are fixed at zero.

best-fit : $\sin^2\theta_{23} = 0.50$

Solar terms on :

The 1-2 parameters are scanned.

best-fit : $\sin^2\theta_{23} = 0.52$
$(\sin^2 2\theta_{23} = 0.9984)$

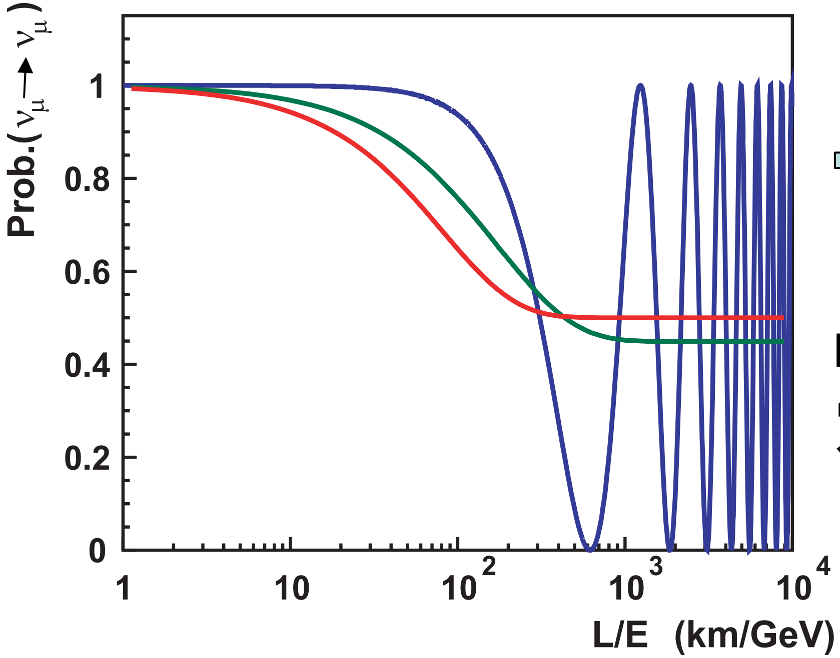
L/E analysis

Survive probability

Neutrino oscillation : $P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 L}{E})$

Neutrino decay : $P_{\mu\mu} = (\cos^2\theta + \sin^2\theta \times \exp(-\frac{m}{2\tau}\frac{L}{E}))^2$

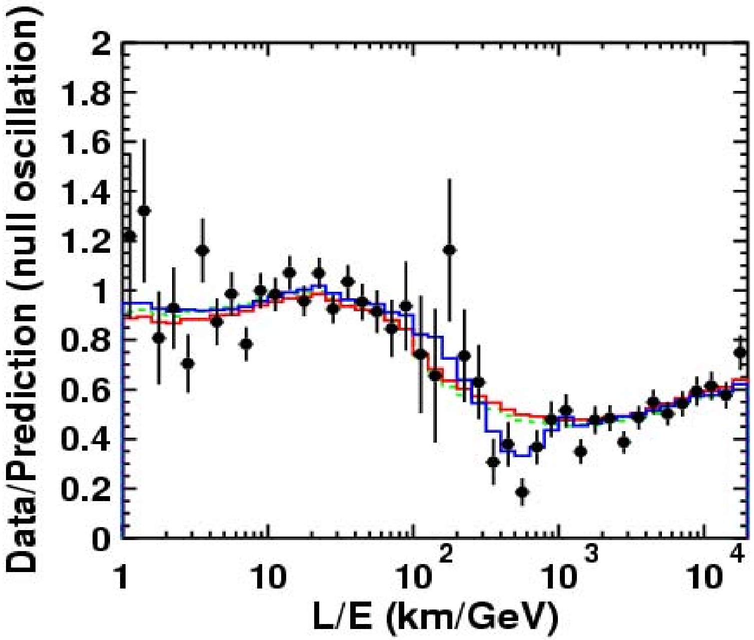
Neutrino decoherence : $P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \times (1 - \exp(-\gamma_0 \frac{L}{E}))$



The first dip can be observed

neutrino decay, decoherence は否定する事ができる。

Tests for neutrino decay & decoherence



Best fit parameters

$\Delta m^2=2.3\times10^{-3}, \sin^2 2\theta=1.00$

$\chi^2_{min}=83.9/83$ d.o.f

($\sin^2 2\theta=1.03$, $\chi^2_{min}=83.4/83$ d.o.f)

$2.0\times10^{-3} < \Delta m^2 < 2.8\times10^{-3}$ eV^2

$0.93 < \sin^2 2\theta$ at 90% C.L.

Oscillation	χ^2_{osc}	= 83.9/83 d.o.f	SK-I
Decay	χ^2_{dcy}	= 107.1/83 d.o.f, $\Delta\chi^2$ = 23.2(**4.8** σ)	3.4 σ
Decoherence	χ^2_{dec}	= 112.5/83 d.o.f, $\Delta\chi^2$ = 27.6(**5.3** σ)	3.8 σ

ν_τ appearance

$\nu_\mu \rightarrow \nu_\tau$ 振動

τ neutrino event selection criteria:

(1) Fiducial Volume: 2m from the ID PMTs (FC events)

(2) Visible Energy (Evis) > 1.33 GeV (Multi-GeV events)

(3) Most energetic ring is electron-like. (Showering events)

Approximately 90% of the backgrounds are rejected.

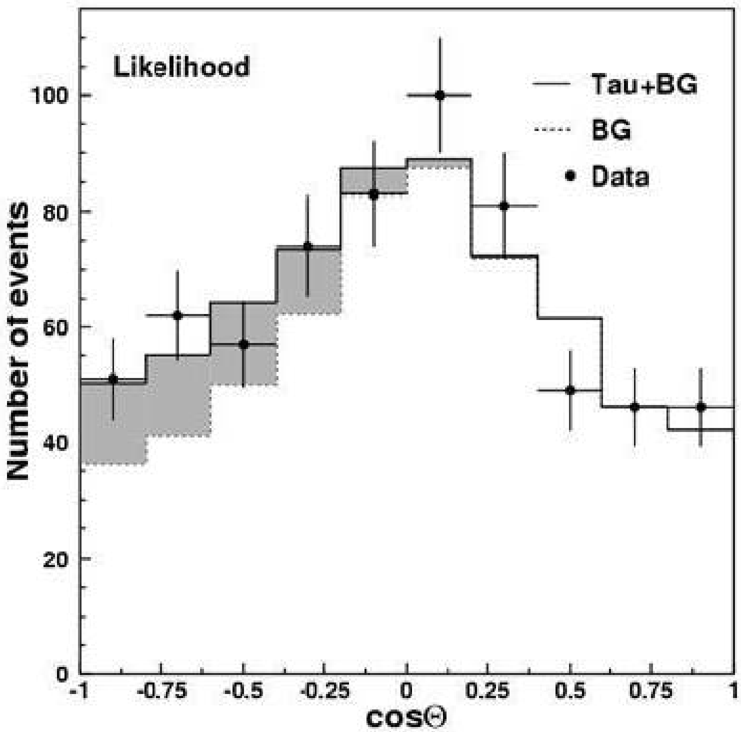
↓

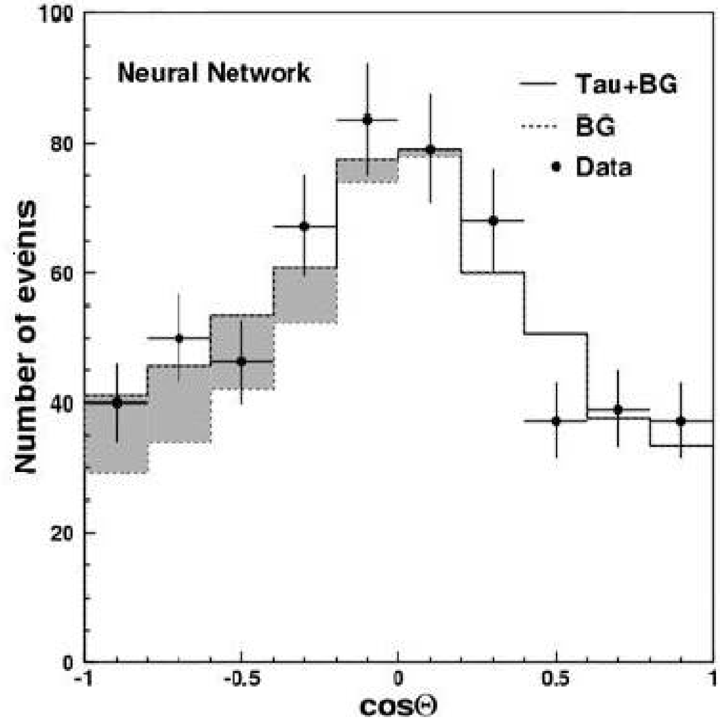
Likelihood or **Neural Network** analysis

These two statistical methods are employed independently.

ν_τ appearance

SK-I

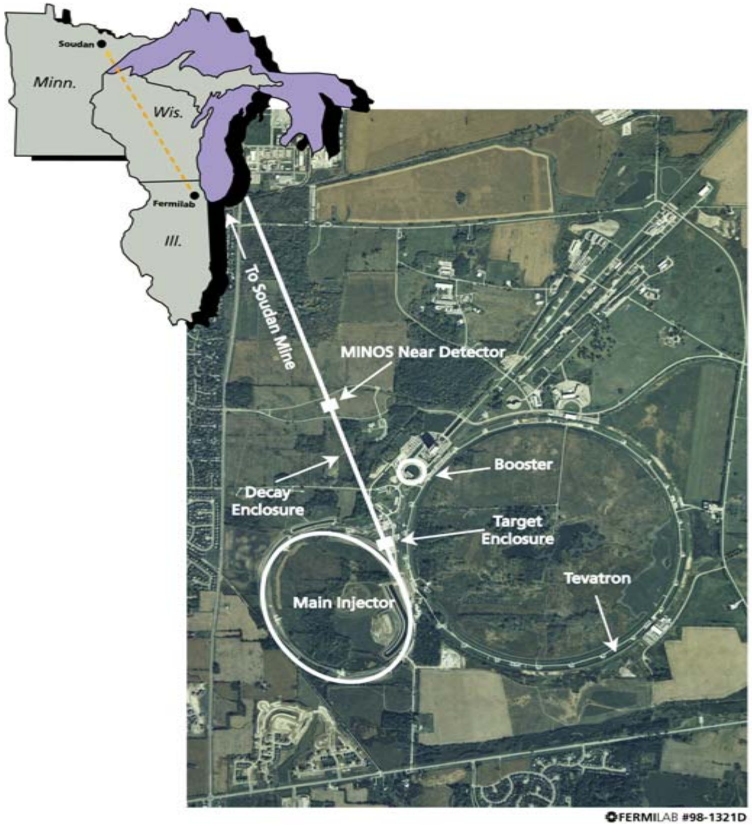


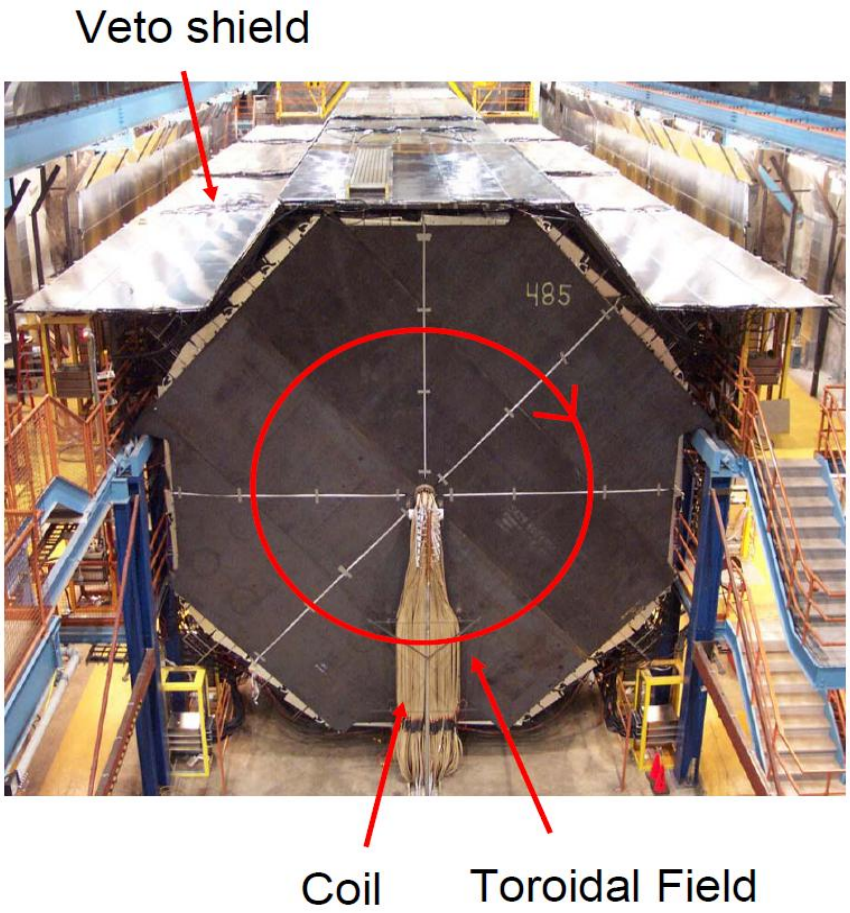


- Likelihood analysis:
  - Total τ excess: 138 ± 48(stat.) + (+14.8/-31.6)(sys.) (2.4 sigma)
  - Expected τ excess: 78.4 ± 26(sys.)
- Neural Net analysis:
  - Total τ excess: 134± 48(stat.) + (+16.0/-27.2)(sys.) (2.4sigma)
  - Expected τ excess: 78.4 ± 27(sys.)

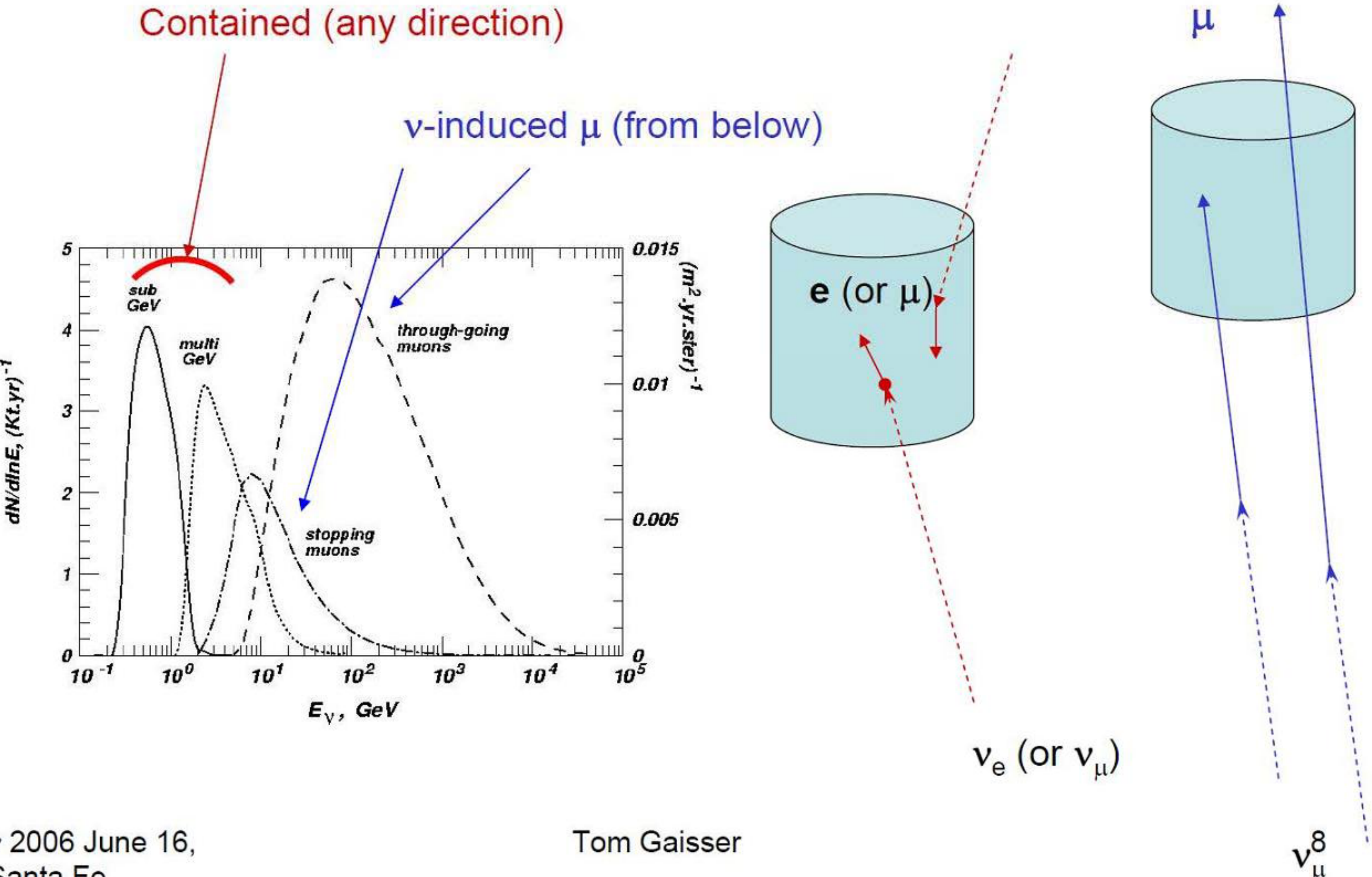
MINOS&SNO@Neutrino 2006

MINOS

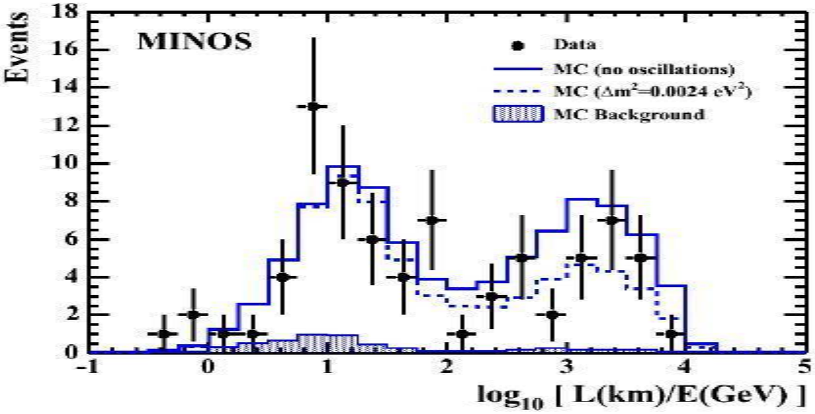

Soudan
Minn.
Wis.
Fermilab
Ill.
To Soudan Mine
MINOS Near Detector
Booster
Decay Enclosure
Target Enclosure
Tevatron
Main Injector
FERMILAB #98-1321D

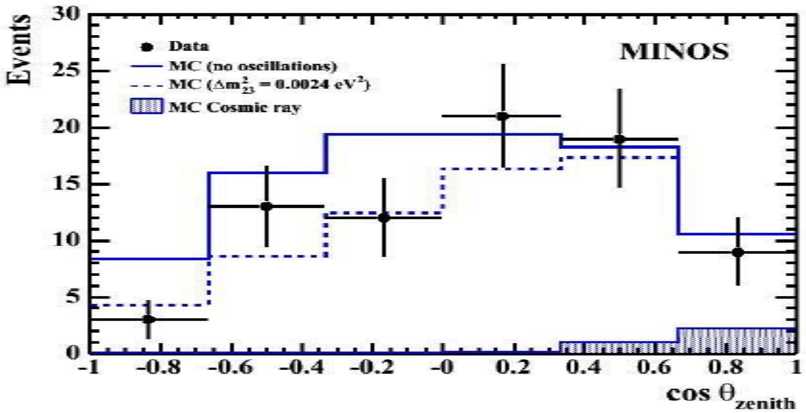

Veto shield
485
Coil
Toroidal Field

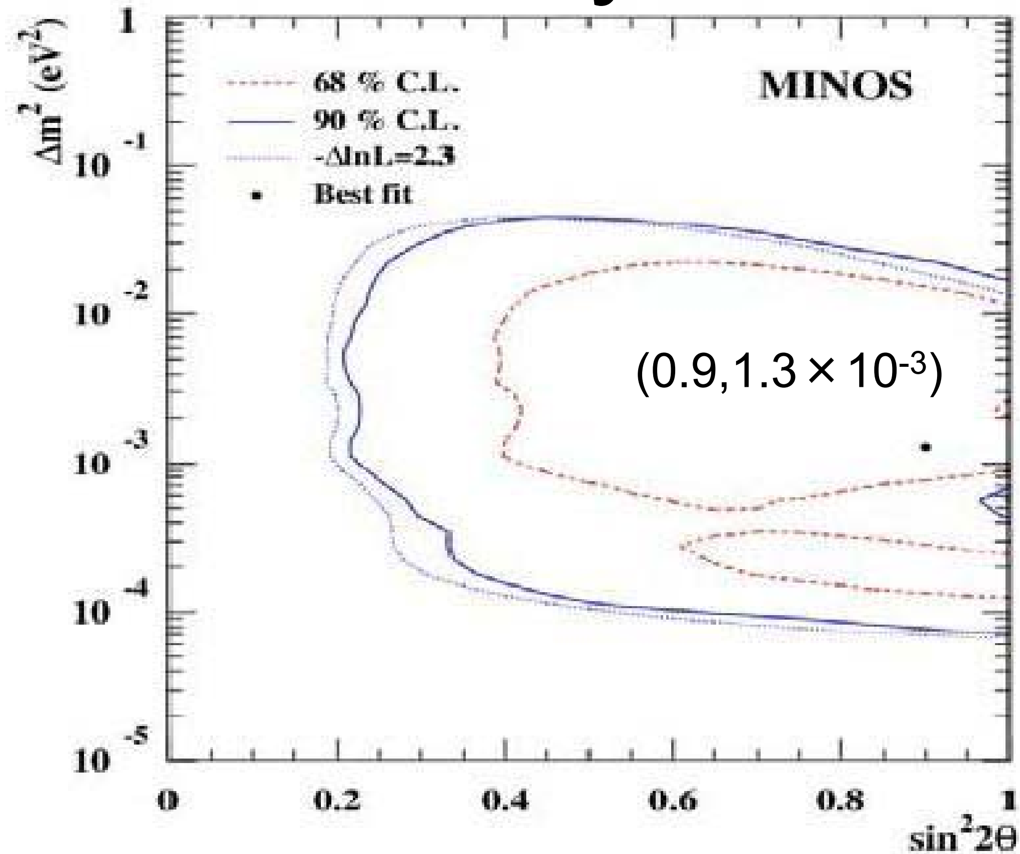
Classes of atmospheric ν events



Contained Vertex Analysis





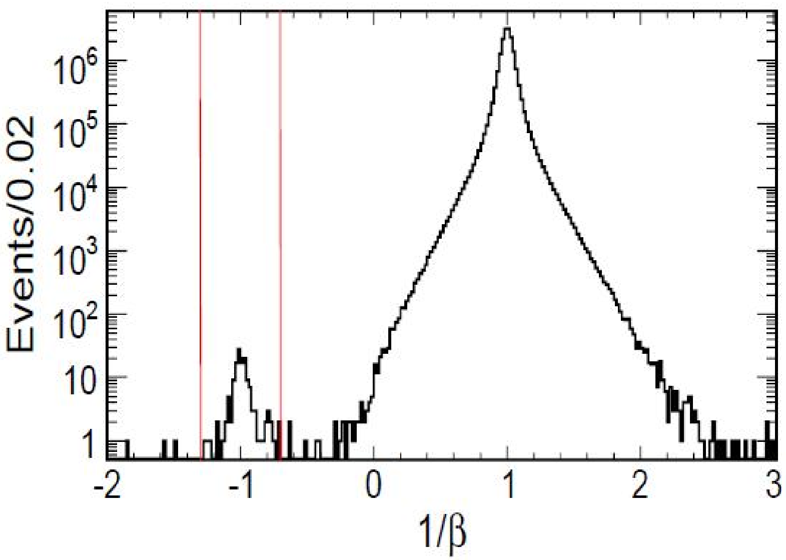


- 107 data events compared with 127 ± 13 expected for no oscillations
- Event direction measured by timing
- 77 events with a well measured direction, 49 downward going, 28 upward going

$$R^{data}_{up/down} / R^{MC}_{up/down} = 0.62\ ^{+0.19}_{-0.14}\ \text{(stat.)} \pm 0.02\text{(sys.)}$$

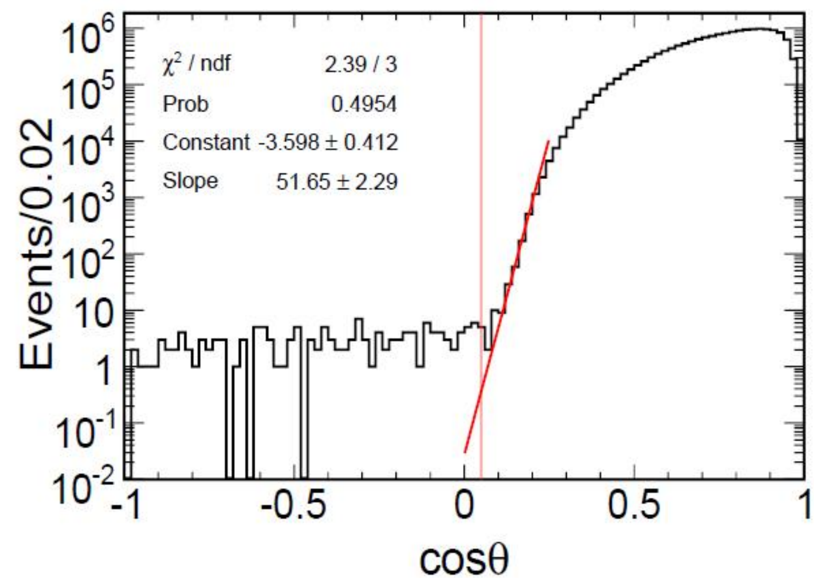
- An extended maximum likelihood analysis with Feldman-Cousins style error analysis yields the above allowed regions

Neutrino induced μ Analysis



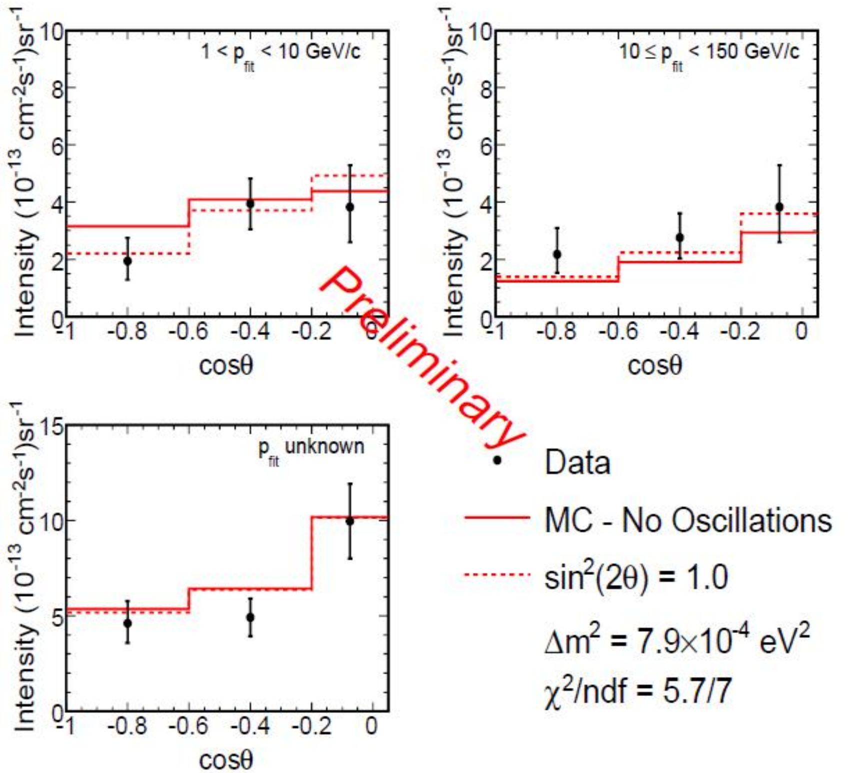
- Upward going μ are produced by ν interactions in the surrounding rock
- μ direction determined by timing
- Single hit timing resolution 2.3 ns
- 131 upward going μ selected

- Soudan overburden is flat
- Horizontal cosmic ray μ have to traverse a large column of rock and are absorbed.
- Cut at a zenith angle of 0.05
- 10 extra neutrino induced μ not selected by the timing cut



Combined Charge Analysis

- Divide data into three categorie
  1. $1 < P_\mu < 10$ GeV/c (low)
  2. $10 < P_\mu < 150$ GeV/c (high)
  3. Poorly measure momentum and charge sign (mostly high momentum)



	μ^+	μ^-
$1<p_\mu<10$Gev/c	22(39.5)	16(20.9)
$10<p_\mu<150$GeV/c	20(18.8)	13(9.7)
Unknown charge	70(81.4)	

Data (MC no oscillations)

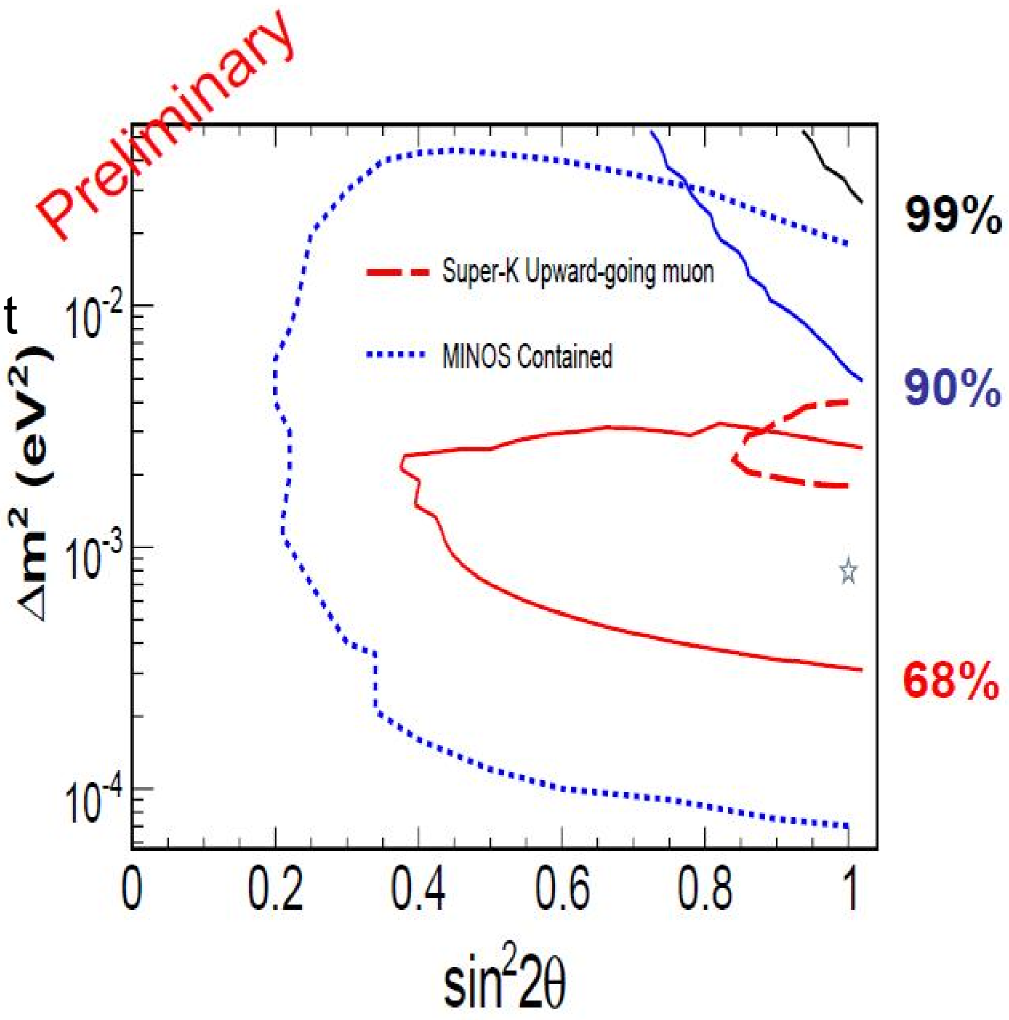
$$\frac{R^{data}_{\frac{low}{high}}}{R^{MC}_{\frac{low}{high}}} = 0.54^{+0.17}_{-0.13}(stat) \pm 0.10(syst)$$

Oscillation analysis

- Oscillation fit to the momentum separated zenith angle distribution
- Five systematic errors included

as nuisance parameters in the fit

  - Reconstruction
  - Cross sections
- Oscillation analysis, best fit point
  - $\Delta m^2 = 7.9 \times 10^{-4}\ eV^2$
  - $\sin^2 2\theta = 1.0$
  - $\chi^2/ndf = 5.7/7$
- No oscillations excluded at the 87% confidence level



Charge Separated Analysis

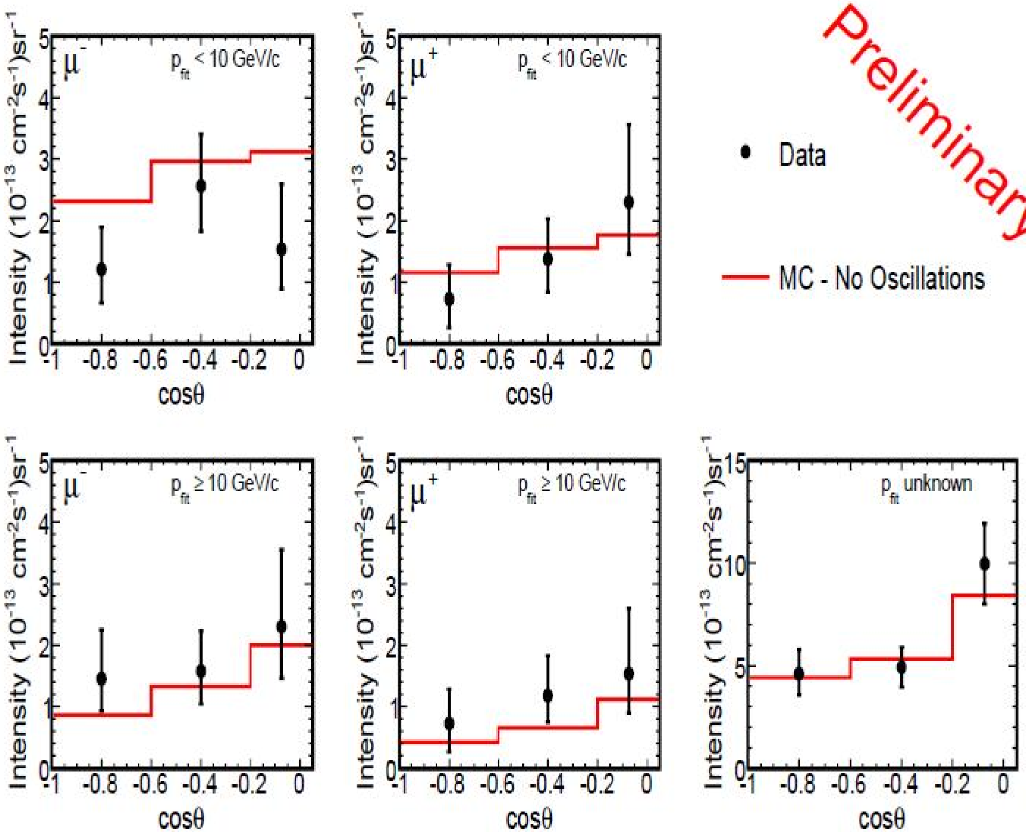
- Both ν_μ and $\bar{\nu}_\mu$ show a deficit with respect to the prediction
- Ratio consistent with 1.0 but with a large uncertainty

$$\left(\frac{R^{data}_{\frac{low}{high}}}{R^{MC}_{\frac{low}{high}}} \right)_{\nu} = 0.53^{+0.22}_{-0.16}(\boldsymbol{stat}) \pm 0.10(\boldsymbol{syst})$$

$$\left(\frac{R^{data}_{\frac{low}{high}}}{R^{MC}_{\frac{low}{high}}} \right)_{\bar{\nu}} = 0.57^{+0.32}_{-0.20}(\boldsymbol{stat}) \pm 0.10(\boldsymbol{syst})$$

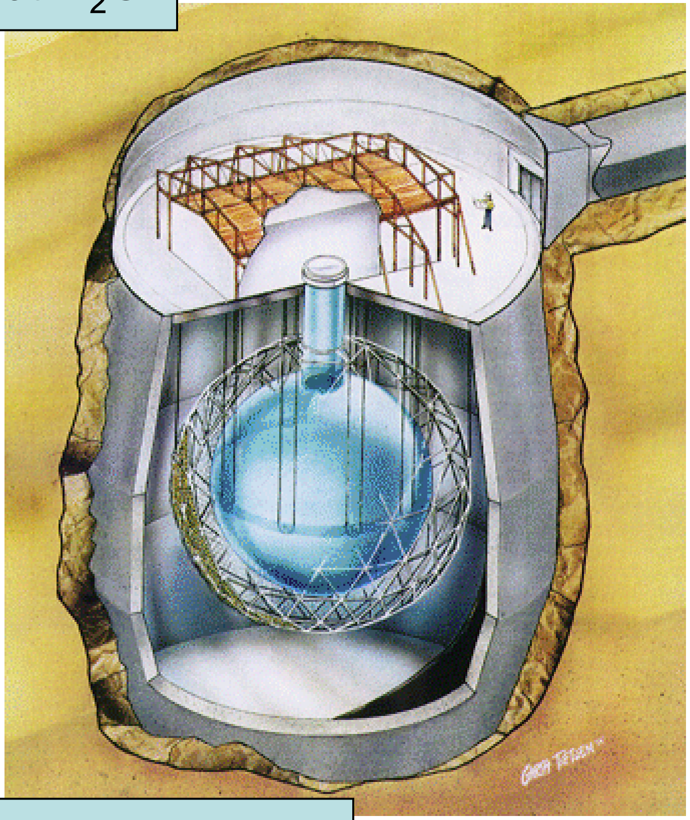
Preliminary

$$R_\nu / R_{\bar{\nu}} = 0.91^{+0.64}_{-0.42}(\boldsymbol{stat}) \pm 0.05(\boldsymbol{syst})$$



SNO

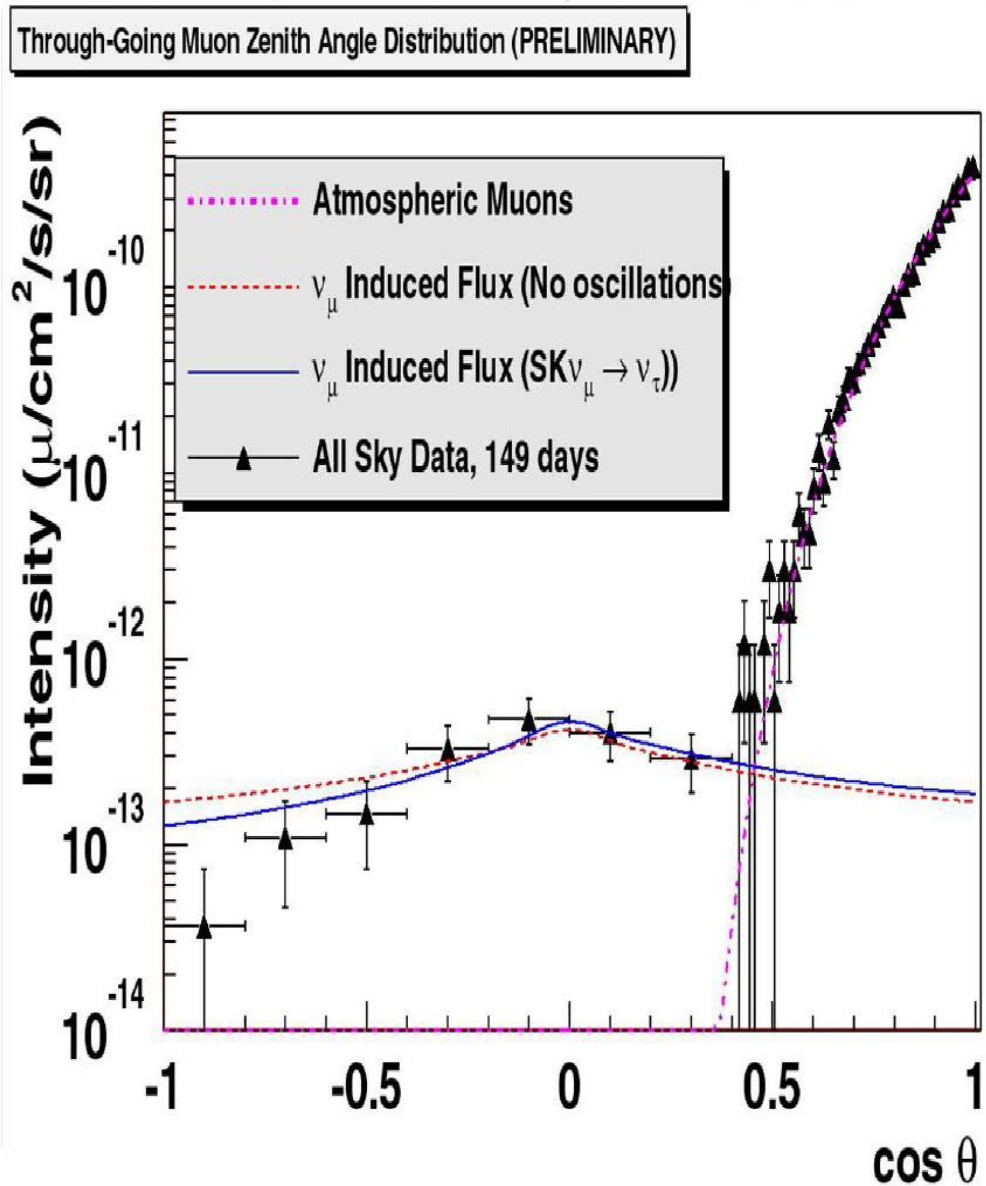
1000t D_2O



2094 m under ground

SNO Atmospheric ν

- SNO is a very deep experiment
- Cosmic μ are absorbed a long way above the horizontal
- Neutrino induced μ from the surrounding rock are visible well above the horizon
- See the transition region where the oscillation dip is maximal
- Data from the first 149 days exposure is available
- Remaining data is still in a blinded analysis



summary

- 全ての大気ニュートリノデータで2世代振動($\nu_\mu \rightarrow \nu_\tau$)に矛盾がない。
- SK:@90C.L.

  $1.9 \times 10^{-3}\ eV^2 < \Delta m^2 < 3.1 \times 10^{-3}\ eV^2$

  $\sin^2 2\theta > 0.93$
- 太陽効果($\nu_\mu \rightarrow \nu_e$ 振動) の有意な結果は見えていない。